

# COMBUSTION EXPLOSIONS

WHOOSH

THUMP

on BANG

- NFPA 921: Chapter 21
- Kirk's Fire Investigation, 7<sup>th</sup> Ed.



- 921: The sudden conversion of potential energy (chemical or mechanical) into kinetic energy with production and release of gases under pressure, or the release of gas under pressure...
- Kirk's: The sudden conversion of potential energy (chemical or mechanical) into kinetic energy with the production of heat, gases, and mechanical pressure.
- Key elements: High energy gases, release or production, suddenness.

## 921 Definitions (2011)

- 21.1.3 Explosion: For fire and explosion investigations, an explosion is the sudden conversion of potential energy (chemical or mechanical) into kinetic energy with the production and release of gas(es) under pressure. These gases then do the mechanical work, such as defeating their confining vessel or moving, changing, or shattering nearby materials
- 21.1.4: Although an explosion is almost always accompanied by the production of a loud noise, the noise itself is not an essential element in the definition of an explosion. The generation and violent escape of gases are the primary criteria of an explosion

## 921 Definitions

- 21.2: Types of explosions. There are two major types of explosions with which investigators are routinely involved: mechanical and chemical, with several subtypes within these types. These types are differentiated by the source or mechanism by which the blast overpressure is produced.

## Kirk's (2012)

- Really, four basic types:
  - Chemical (reactions: deflagration and detonation)\*
  - Mechanical (no chemical change of state)
  - Electrical (rapid discharge causing localized heating – from a weak arc to a lightning bolt)
  - Nuclear – lots of heat and subatomic reactions (we WON'T be investigating these!)

\*Most produce gases and heat with the heat causing rapid expansion of those gases.  
A few produce only heat and no gases (solids only).

## 921 Definitions

- 21.2.3.1 Chemical explosions: The generation of the overpressure is the result of exothermic reactions wherein the fundamental chemical nature of the fuel is changed. Chemical reactions of the type involved in an explosion usually propagate in a reaction front away from the point of initiation.

## DEFLAGRATION

- THERMAL PROCESS
- SUBSONIC FLAME/REACTION PROPAGATION

## 921 Definitions

- 23.1.3.2 Flash fires: A flash fire is a fire that spreads rapidly through a diffuse fuel such as dust, gas, or the vapors of an ignitable liquid, without the production of damaging pressure. The ignition of diffuse fuels does not necessarily always cause explosions. Whether an explosion occurs depends on the location and concentration of diffuse fuels and on the geometry, venting, and strength of the confining structure or vessel, if present and the presence of obstacles.



- Deflagration of Vapor from 1 gal of gasoline



## Deflagration

- Relatively low pressures (<100psi)
- Slowly Developing (100-500ms)
- Large pieces
- Generalized damage

## DETONATION:

- MECHANICAL PROCESS – SHOCK WAVE PROPAGATION  
Pressure/heat causes reaction
- PROPAGATION IS SUPERSONIC IN THAT MEDIUM (over 1000 m/s in most)

## Detonation

- ½ lb Military dynamite in cabinet
- Localized shattering and splintering
- Cabinet destroyed but nearby cabinets unaffected

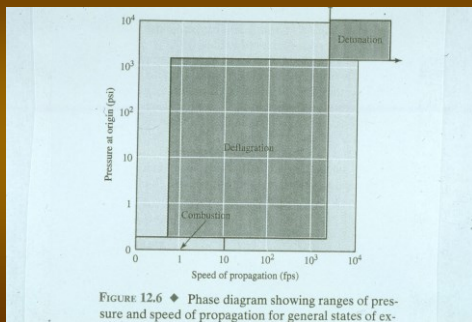


## Detonation of ¼ lb. C4 in Oven

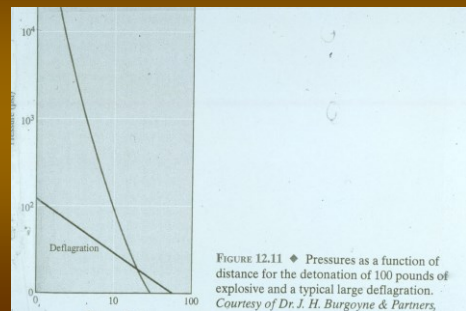
- Very high pressures (>100,000psi at surface)
- Very rapid development (10-500µs)
- Localized shattering



## Pressure and Speed of Propagation



## Pressures v. Distance



## DIFFUSE PHASE EXPLOSIONS

FUEL GASES OR VAPORS  
PRE-MIXED WITH AIR  
AND THEN IGNITED

## Vapor Density

- Calculated from the ratio of molecular weight of chemical divided by the molecular weight of air
- V.D. =  $\frac{\text{Molecular weight of vapor}}{\text{Molecular Weight of Air}}$

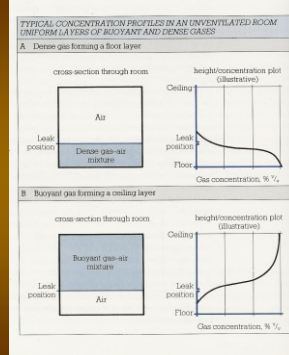
Molecular weight of air ~29

## Vapor Density

Table 1: Vapor Densities

| Fuel            | Formula                          | Molecular Weight (MW) | Vapor Density (MW/29) |
|-----------------|----------------------------------|-----------------------|-----------------------|
| Hydrogen        | H <sub>2</sub>                   | 2                     | 2/29 = 0.07           |
| Methane         | CH <sub>4</sub>                  | 16                    | 16/29 = 0.55          |
| Carbon Monoxide | CO                               | 28                    | 28/29 = 0.97          |
| Ethane          | C <sub>2</sub> H <sub>6</sub>    | 30                    | 30/29 = 1.03          |
| Propane         | C <sub>3</sub> H <sub>8</sub>    | 44                    | 44/29 = 1.51          |
| Butane          | C <sub>4</sub> H <sub>10</sub>   | 58                    | 58/29 = 2.00          |
| Pentane         | C <sub>5</sub> H <sub>12</sub>   | 72                    | 72/29 = 2.48          |
| Hexane          | C <sub>6</sub> H <sub>14</sub>   | 86                    | 86/29 = 2.97          |
| Diethyl Ether   | C <sub>4</sub> H <sub>10</sub> O | 74                    | 74/29 = 2.55          |
| Natural Gas     | Varies                           | ---                   | 0.6 - 0.8             |
| LP Gas          | Varies                           | ---                   | 1.5 - 2               |
| Gasoline Vapors | Varies                           | ---                   | 2.5 - 4               |

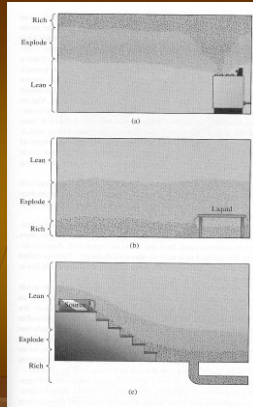
## Effects of vapor density on distribution of gas in still air



From Harris, 1983

## Vapor Density

- Natural Gas – mixes and forms gradient
- Vapors of Liquid – sink to floor, steep gradient
- Heavy vapors flow down and fill
- They also flow outwards on a level surface like a liquid



## Combustion Explosions in Stratified Fuel/Air Mixtures

- Hexane Fuel
- Allowed to evaporate
- 20m<sup>3</sup> room
- Fuel Tray on Floor
- Pressure transducers on floor, ceiling, walls
- 1m<sup>2</sup> vent panel
- Electric arc ignition

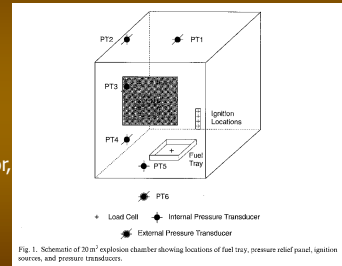


Fig. 1. Schematic of 20 m<sup>3</sup> explosion chamber showing locations of fuel tray, pressure relief panel, ignition sources, and pressure transducers.

## Combustion Explosions in Stratified Fuel/Air Mixtures

Table 1  
Summary of experimental conditions

| Test | Ambient temperature (°C) |      | Evaporation time (min) | Approximate hexane mass loss (g) <sup>a</sup> | Ignition sequence    |
|------|--------------------------|------|------------------------|---|----------------------|
|      | Chamber                  | Fuel |                        |   |                      |
| 1    | 11                       | 19   | 13                     | 136   | All                  |
| 2    | 19                       | 18   | 14                     | 139   | 1,2,3,4 <sup>b</sup> |
| 3    | 26                       | 19   | 15                     | 130   | 3,4 <sup>b</sup>     |
| 4    | 33                       | 21   | 20                     | 158   | 3 <sup>b</sup> , 4   |
| 5    | 34                       | 22   | 20                     | 153   | 1,2,3 <sup>b</sup>   |

<sup>a</sup> These values incorporate a correction for the variation (drift) in the power supply to the load cell output. Values should be considered accurate to  $\pm 15\%$ .

<sup>b</sup> This denotes the igniter that was identified from the video record as having achieved ignition.

- Summary of Test Conditions

## Stratified Fuel/Air Mixtures

- Top: Averaged signals from 5 transducers
- Bottom: Overlay of signals, showing same magnitude and co-incidence in time ( $\pm 5\text{ms}$ )

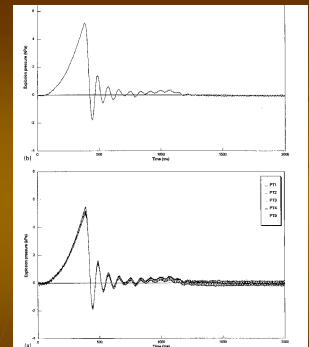
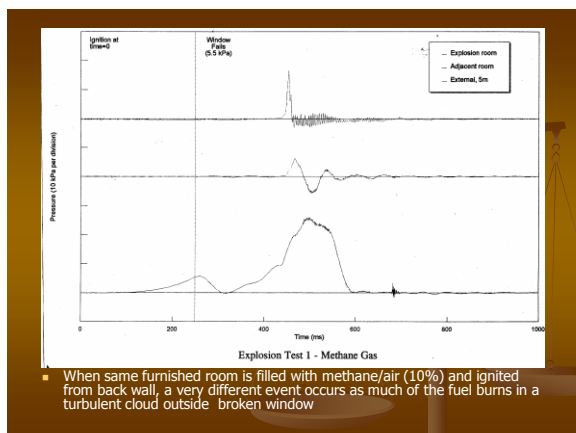
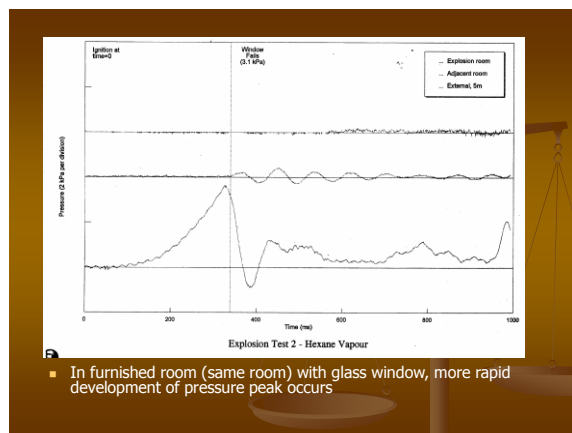
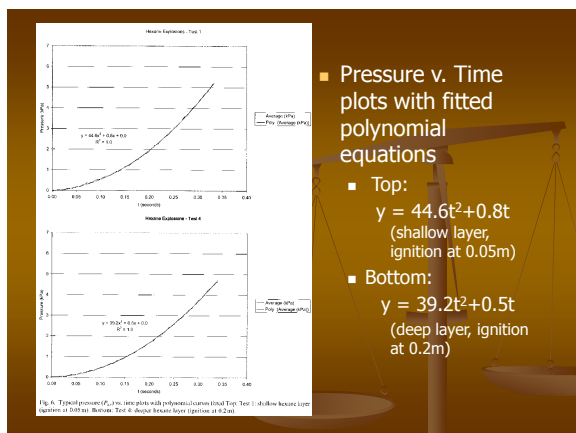
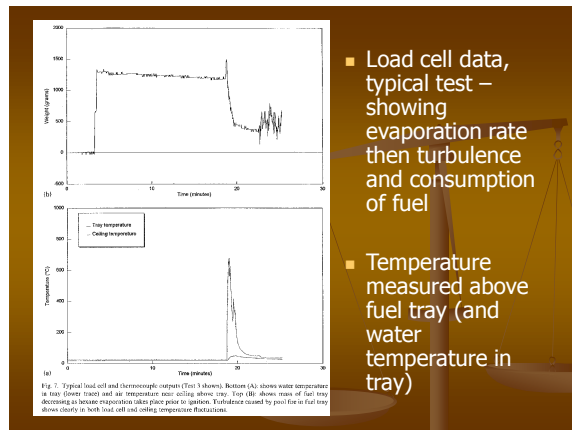
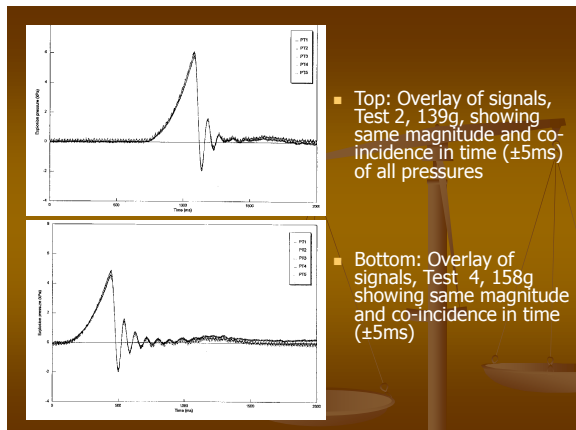


Fig. 2. Pressure time history—Test 1. (Top) of a hexane fuel leak (ignited by electric arc) showing pressure peak and oscillations of air pressure in room after the pressure transducers. Bottom (b) overlay of individual signals from pressure transducers (PT1-PT5) showing coincidence of time and magnitude. Top (a) averaged composite signal from same transducers.





EXPLOSION PRESSURES :

| LOCATION                 | MEASUREMENT                    | PRESSURE (kPa) |
|--------------------------|--------------------------------|----------------|
| Explosion Room (ceiling) | Maximum positive pressure      | 3.7            |
|                          | Maximum negative pressure      | -0.9           |
|                          | Pressure at which glass failed | 3.1            |
|                          | Maximum positive pressure      | 0.4            |
| Adjacent Room (ceiling)  | Maximum positive pressure      | -0.3           |
|                          | Maximum negative pressure      | <0.2           |

Hexane Layer

EXPLOSION PRESSURES :

| LOCATION                 | MEASUREMENT                    | PRESSURE (kPa) |
|--------------------------|--------------------------------|----------------|
| Explosion Room (ceiling) | Peak 1 maximum pressure        | 5.9            |
|                          | Peak 2 maximum pressure        | 26.1           |
|                          | Pressure at which glass failed | 5.5            |
|                          | Maximum positive pressure      | 6.3            |
| Adjacent Room (ceiling)  | Maximum positive pressure      | -5.6           |
|                          | Maximum negative pressure      | 16.7           |

Methane

## Combustion Explosions in Stratified Fuel/Air Mixtures

- Conclusions:
  - Evaporation produces discrete, floor-level layer requiring direct contact with ignition source.
  - Pressure in a normal-size, normal proportioned room develops at a t-squared rate
  - Pressure equilibrates at the speed of sound; in a normal-size, normally proportioned room this means all portions of the room receive equal pressure at the same time
  - Equal overpressure will cause failure where the structure is weakest no matter where the pre-blast fuel/air mixture is.

## Upon Ignition:

- Only vaporized fuel contributes to blast
- (Liquid fuels don't burn)
- Residual liquid contributes to post-blast fire
- So distribution of THERMAL damage may be useful!

## We Have to Estimate How Much Fuel is in Vapor State

- Depends on vapor pressure, time, and temperature
- What was the fuel?
- How much was it?
- How was used?
- What were the starting conditions?

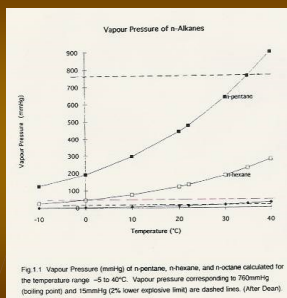
## Evaporating Liquids

- Vapor Pressure
- Temperature of Surface
- Nature of Surface
- Area of Spill or Pour (Pool)
- Drafts/Ventilation

## Vapor Pressure

- If vapor pressure is below the LEL equivalent (2% of 760mmHg – 15mmHg) (lower dashed line), there can be no propagation.
- If the vapor pressure\* is above the UEL equivalent (8% of 760mmHg – 60mmHg) (red dashed line), there can be no propagation.

\*at saturation



## EXPLOSIVE LIMITS

- LEL = Lower Explosive Limit
- LFL = Lower Flammability Limit

Not exactly the same, but used interchangeably

## LEAN MIXTURES

- Produce slower flame velocities
- Little Heat Loss
- No Continuing (post-blast) Flame

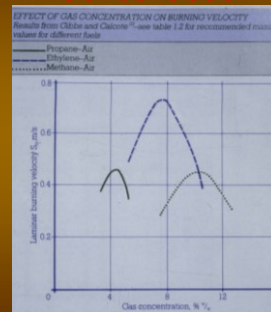
## EXPLOSIVE LIMITS

- UFL = Upper flammability limit
- UEL = Upper Explosive Limit

## RICH MIXTURES

- Produce Slower Flame Velocities
- Radiant Heat Loss (Soot)
- Continuing Flame  
(especially above pools of liquid fuel)

## Burning Velocity is Dependent on Concentration



## ■ STOICHIOMETRIC MIXTURE

## ■ IDEAL MIXTURE

- Perfect balance – after reaction there is no fuel and no oxygen remaining

## EXPLOSIVE RANGE

- (not the place you go to blow things up!)
- The Range of Concentration (in air) for Ignition to Take Place – at a particular temperature

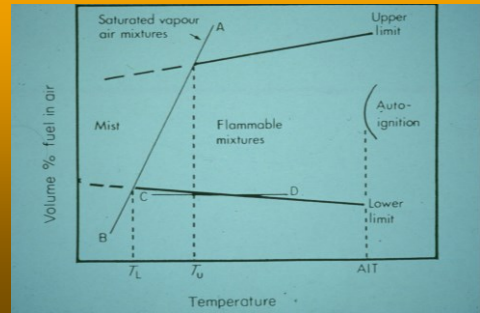
## Flammability Limits

Table 2: Flammability Limits at 20°C

| Fuel            | LEL   | UEL          | Auto-Ignition Temperature |
|-----------------|-------|--------------|---------------------------|
| Natural Gas     | 4.7%  | 15.0%        | 482-632°C (900-1170°F)    |
| Butane          | 1.9%  | 8.5%         | 482-638°C (900-1000°F)    |
| Acetylene       | 2.5%  | 81 (to 100%) | 305°C (580°F)             |
| Diethyl Ether   | 1.9%  | 36.0%        | 160°C (320°F)             |
| Gasoline        | 1.4%  | 7.6%         | 280°C (536°F) *           |
| Petroleum Ether | 1.1%  | 5.9%         | 288°C (550°F)             |
| Carbon Monoxide | 12.5% | 74.0%        | 609°C (1128°F)            |
| Acetone         | 2.15% | 13.0%        | 465°C (870°F)             |
| Coleman Fuel    | 1.5%  | 7.4%         | 335°C (635°F)             |

\* 80 octane.

## Flammable Range is Dependent on Temperature



## EXPLODING MYTHS



That 20 litre HDPE container is full of gasoline

## EXPLODING MYTHS



- Only the gasoline pooled around the cap is burning

## EXPLODING MYTHS



- 10min after ignition – small flame at cap

## EXPLODING MYTHS



- 17 min - Top of HDPE container has melted

## EXPLODING MYTHS



- 20 min – Entire surface of gasoline, 250kW

## EXPLODING MYTHS



- 21 min – container overflowing

## EXPLODING MYTHS



- 23 min – Container collapsing, 500+kW

## EXPLODING MYTHS



Photo 01 - ignition

- 10 litre plastic gas can on its side, one-half full, open top

## EXPLODING MYTHS

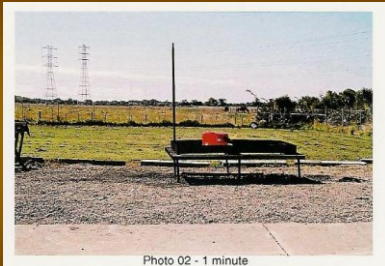


Photo 02 - 1 minute

Small quiet flame issuing from neck at 1 min

## EXPLODING MYTHS



Photo 06 - 5 minutes

At 5 min, flame is melting neck and top (side) of container



## EXPLODING MYTHS



At 10 min, flame is growing larger as can fails, but still no explosion

## EXPLODING MYTHS



By 14 min, the entire can is involved, the gasoline spills over and causes a pool fire

## Then, why do we see “gas cans” explode?

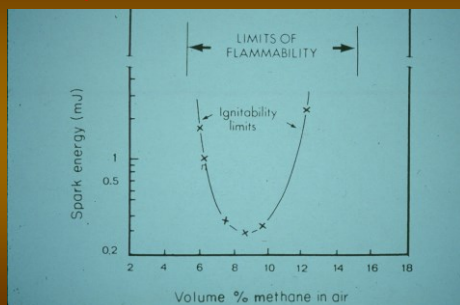
- Special conditions where the vapor/air mixture is not in saturation
  - VERY cold conditions
  - Can almost empty
  - Can being quickly emptied onto a flaming fire
  - It's NOT gasoline: alcohols (and others) have a wider flammability range and a LOWER vapor pressure at “normal” temperatures. E85 motor fuel is 85% ethanol!

## IGNITION ENERGY

v.

## IGNITION TEMPERATURE

## Minimum Ignition Energy is Dependent on Concentration



## Minimum Ignition Energy

- Measured in a special lab apparatus for reproducibility
- Uses an electrical arc whose energy can be carefully controlled (capacitance and duration)
- Arc is in middle of volume so all energy released is absorbed by nearby fuel – maximizing energy transfer
- Data not easily transferable to ignition of solid fuels by “weak” sources

## IGNITION REQUIRES

- Fuel in Appropriate Form (Concentration)
- Source has Enough Energy
- There is Contact Between Fuel and Source
- Contact is of Sufficient Duration (20ms for gasoline)

## Ignition Temperature v. Energy: GASES

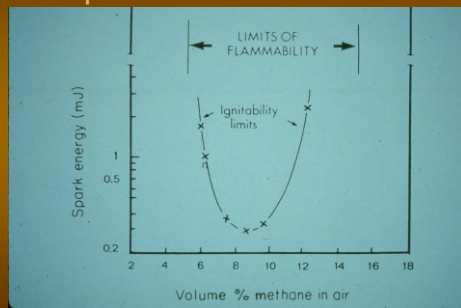
TABLE 4.1 ♦ Flammability (Explosive) Limits and Ignition Temperatures of Common Gases

| Fuel                       | Explosive Limits (In Air) |       | Ignition Temperature (Minimum) |           | Minimum Ignition Energy mJ |
|----------------------------|---------------------------|-------|--------------------------------|-----------|----------------------------|
|                            | Lower                     | Upper | °C                             | °F        |                            |
| Natural gas                | 4.5                       | 15    | 482-632                        | 900-1,170 | 0.25                       |
| Propane (commercial)       | 2.15                      | 9.6   | 493-604                        | 920-1,120 | 0.25                       |
| Butane (commercial)        | 1.9                       | 8.5   | 482-538                        | 900-1,000 | 0.25                       |
| Acetylene                  | 2.5                       | 81*   | 305                            | 581       | 0.02                       |
| Hydrogen                   | 4                         | 75    | 500                            | 932       | 0.01                       |
| Ammonia (NH <sub>3</sub> ) | 16                        | 25    | 651                            | 1,204     | —                          |
| Carbon monoxide            | 12.5                      | 74    | 609                            | 1,128     | —                          |
| Ethylene                   | 2.7                       | 36    | 490                            | 914       | 0.07                       |
| Ethylene oxide             | 3                         | 100   | 429                            | 804       | 0.06                       |

Sources: NFPA, *NFPA Fire Protection Handbook*, 17th ed. NFPA, Quincy, MA, 1991, Table 3-7c; and *SFPE Handbook of Fire Protection Engineering*, 2nd ed. NFPA, Quincy, MA, 1995, Table 3-16.2.

\*Higher concentrations (up to 100) may detonate.

## Minimum Ignition Energy is Dependent on Concentration



## Ignition Temperature v. Energy: VAPORS

TABLE 4.2 ♦ Minimum Autoignition Temperatures and Flammable Ranges of Some Common Ignitable Liquids

| Fuel                   | Temperature (°C) | Temperature (°F) | Minimum Ignition Energy (mJ) | Flammable Range (% In Air @ 20°C) |
|------------------------|------------------|------------------|------------------------------|-----------------------------------|
| Acetone                | 465              | 869              | 1.15                         | 2.4-12.8                          |
| Benzene                | 498              | 928              | 0.2                          | 1.4-7.1                           |
| Dichloro ether         | —                | —                | —                            | 1.8-36.0                          |
| Ethanol (100 percent)  | 363              | 685              | —                            | —                                 |
| Ethylene glycol        | 398              | 748              | —                            | —                                 |
| Fuel oil #1 (kerosene) | 210              | 410              | —                            | —                                 |
| Fuel oil #2            | 257              | 495              | —                            | —                                 |
| Gasoline (low octane)  | 280              | 536              | —                            | 1.4-7.6                           |
| Gasoline (100 octane)  | 456              | 853              | —                            | 1.5-7.6                           |
| Jet fuel (JP-6)        | 230              | 446              | —                            | —                                 |
| Linseed oil (boiled)   | 206              | 403              | —                            | —                                 |
| Methanol               | 464              | 867              | 0.14                         | 6.7-36.0                          |
| n-pentane              | 260              | 500              | 0.22                         | 1.5-7.8                           |
| n-hexane               | 225              | 437              | 0.24                         | 1.2-7.5                           |
| n-heptane              | 204              | 399              | —                            | —                                 |
| n-octane               | 206              | 403              | —                            | 1.0-7.0                           |
| n-decane               | 210              | 410              | —                            | —                                 |
| Petroleum ether        | 288              | 550              | —                            | 1.1-5.9                           |
| Pinene (alpha)         | 255              | 491              | —                            | —                                 |
| Turpentine (spirit)    | 253              | 488              | —                            | —                                 |

Sources: Data taken from NFPA, *Fire Protection Guide to Hazardous Materials*, 12th ed. NFPA, Quincy, MA, 1997; Tamm, C. E., and McVeety, J. W. *The Chemistry of Fire and Hazardous Materials*. Allyn and Bacon, Boston, 1981.

## Ignition of Solids

| Material                           | $h_p/c$<br>(kW/m <sup>2</sup> ·s) | $T_{ig}$<br>(°C) | $d''_{critical}$<br>(mm/m <sup>2</sup> ) |
|------------------------------------|-----------------------------------|------------------|--|
| Plywood, plain (0.635cm)           | 0.46                              | 390.             | 16.                                      |
| Plywood, plain (1.27cm)            | 0.54                              | 390.             | 16.                                      |
| Plywood, FR (1.27cm)               | 0.76                              | 620.             | 44.                                      |
| Hardboard (6.35mm)                 | 1.87                              | 298.             | 10.                                      |
| Hardboard (3.175mm)                | 0.88                              | 365.             | 14.                                      |
| Hardboard (gloss paint), (5.4mm)   | 1.22                              | 400.             | 17.                                      |
| Hardboard (nitrocellulose paint)   | 0.79                              | 400.             | 17.                                      |
| Particleboard (1.27cm stock)       | 0.93                              | 412.             | 18.                                      |
| Douglas Fir particleboard (1.27cm) | 0.94                              | 382.             | 16.                                      |
| Fiber insulation board             | 0.46                              | 355.             | 14.                                      |
| Polyisocyanurate (5.08cm)          | 0.020                             | 445.             | 21.                                      |
| Foam, rigid (2.54cm)               | 0.050                             | 455.             | 20.                                      |
| Foam, flexible (2.54cm)            | 0.32                              | 390.             | 16.                                      |
| Polystyrene (5.08cm)               | 0.38                              | 630.             | 46.                                      |
| Polycarbonate (1.52mm)             | 1.16                              | 528.             | 50.                                      |
| PMMA type G (0.72cm)               | 1.02                              | 578.             | 15.                                      |

## Ignition of Solids

|                                     |      |      |     |
|-------------------------------------|------|------|-----|
| Polystyrene (5.08cm)                | 0.38 | 630. | 46. |
| Polycarbonate (1.52mm)              | 1.16 | 528. | 30. |
| PMMA type G (1.27cm)                | 1.02 | 578. | 15. |
| PMMA polycast (1.59mm)              | 0.75 | 276. | 9.  |
| Carpet #1 (wool, stock)             | 0.11 | 465. | 23. |
| Carpet #2 (wool, untreated)         | 0.25 | 455. | 20. |
| Carpet #2 (wool, treated)           | 0.24 | 455. | 22. |
| Carpet (nylon/wool blend)           | 0.68 | 412. | 18. |
| Carpet (nylon)                      | 0.42 | 300. | 10. |
| Cyprum board, (common) (1.27mm)     | 0.45 | 565. | 55. |
| Cyprum board, FR (1.27cm)           | 0.40 | 510. | 28. |
| Cyprum board, wall paper            | 0.57 | 412. | 18. |
| Asphalt shingle                     | 0.70 | 378. | 15. |
| Fiberglass shingle                  | 0.50 | 445. | 21. |
| Glass reinforced polyester (2.24mm) | 0.52 | 590. | 16. |
| Glass reinforced polyester (1.14mm) | 0.72 | 400. | 17. |
| Aircraft panel, epoxy fiberite      | 0.24 | 505. | 28. |

Source: From Quintiere and Harkness, ref. 4.

Most solids require 350-600°C, 700-1150°F

**TABLE 5.2 ♦ Thermal Properties of Polymeric Materials**

| Natural Polymers              | $\Delta H_f$ | Thermal Behavior (Drysdale)              | Melting Point (°C) (Merek Index) |
|-------------------------------|--------------|--|----------------------------------|
| Wool                          |              | Chars above 200°C                        |                                  |
| Cellulose                     | 16.1         | Chars above 100°C                        |                                  |
| <b>Thermoplastic Polymers</b> |              |  |                                  |
| Polyethylene (HD)             | 46.5         | Melts 130–135°C                          | (85–110) <sup>a</sup>            |
| Polypropylene (Isotactic)     | 46.0         | Melts 160°C                              | (165) <sup>a</sup>               |
| Polymethylmethacrylate        | 26.2         | Melts 160                                | (250)                            |
| Polystyrene                   | 41.6         | Melts 240                                | (180)                            |
| Polycrylonitrile              |              | Melts 317                                |                                  |
| Nylon 66                      | 31.9         | Melts 250–260                            |                                  |
| Nylon 6                       |              | —  | (225)                            |
| Polyvinyl chloride (PVC)      | 19.9         | —  | (Chars 200–300)                  |
| <b>Thermosetting Polymers</b> |              |  |                                  |
| Polyesters                    |              |  | (Dec 250)                        |
| Polyurethane foam             | 24.4         | Decomposes 200–300; polyols, isocyanates |                                  |
| Phenolic foams                | 17.9         | Chars                                    |                                  |
| Polyisocyanurate foams        | 24.4         | Chars                                    |                                  |
| Silicones                     |              |  |                                  |

Source: From Drysdale, D. *An Introduction to Fire Dynamics*, 2nd ed. John Wiley & Sons, Chichester, 1999, 3.  
<sup>a</sup>The melting point of many polymers is determined by the amount of cross-linking between the chemical structures, and can vary considerably.

## Plastics

## Ignition Temperatures: Plastics

**TABLE 5.3 ♦ Autoignition Temperatures of Common Plastics**

| Plastic                      | Minimum Ignition Temperature |         |
|------------------------------|------------------------------|---------|
|                              | °C                           | °F      |
| Polyethylene                 | 365*                         | 488     |
| Polyisocyanate               |                              | 525     |
| Polymethylmethacrylate       | 310*                         | 467     |
| Polypropylene                | 330*                         | 498     |
| Polystyrene                  | 360*                         | 573     |
| Polytetrafluoroethylene      |                              | 660     |
| Polyurethane foam (flexible) |                              | 456–579 |
| Polyurethane foam (rigid)    |                              | 498–565 |
| Polyvinyl chloride           |                              | 507     |

Source: NFPA. *Fire Protection Handbook*, 16th ed. NFPA, Quincy, MA, 1986, 5–126.

\*Babrauskas, V. *Ignition Handbook*. Fire Science Publishers, Issaquah, WA, 2003, 244.

## 21.9 Dust Explosions

- Any finely divided combustible solid can be a fuel
  - Sawdust
  - Sugar, coal, plastic, cork, milk powder, printer toner
- Often sequential/multiple – growing in strength
- Physical agitation often the trigger (in the presence of a continuous ignition source)
  - Vibration, fans, conveyors, demolition
  - Large fires

## 21.9 Dust Explosions

- Ignition sources can be very hard to identify: pilot flames, burners, torches, candles
- Also, static discharges and electrical arcs.
- Hot surfaces: must be very hot BUT the deeper the accumulation of dust, the easier it is to ignite it – first as a fire, fire causes draft, draft stirs dust – BANG!

## 21.10 Smoke Explosions

- Backdrafts
- Must be a large, prolonged fire in under-ventilated conditions causing HOT combustion gases to accumulate
- “Clear” CO-rich rooms as well as fuel-rich black/brown smoke – CO, soot, pyrolysis products all can support backdraft/smoke explosions
- Change in ventilation triggers event if there is a suitable source of ignition present – breaking windows, opening doors, walls collapsing

## 21.11 Unconfined Vapor

- Very large clouds of flammable vapors (usually industrial or transport accident)
- Often start as a flash fire, then confinement from adjacent buildings or even tree lines can alter the development into a deflagration.
- Buncefield (UK) – massive accidental spill of gasoline most recent example.
- Recent railroad tanker incidents, too.
- GexCon modeling very successful in recreating such incidents (pre-blast and explosion itself)

## IGNITION SOURCES

- ❖ Continuous
- ❖ Intermittent

## CONTINUOUS SOURCES



- Pilot flame produces minimal air current but is "on" all the time
- Main burner produces draft to draw vapors in but is not on all the time



- Many furnaces are electric ignition and provide no ignition source until the thermostat calls for heat
- So be SURE.

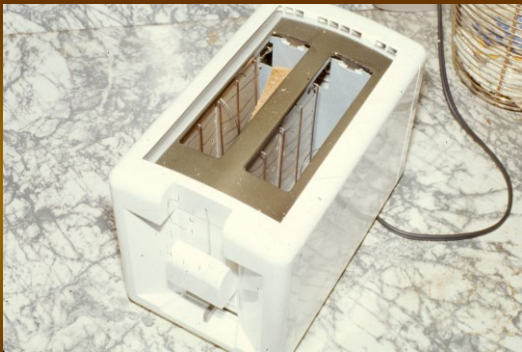


- Kitchen burners may represent continuous hot surface or flame ignition sources. Food/oil is a flame source!

## Hot Surfaces

## How HOT Does It Have to BE?

- Not just simply at or above the listed autoignition temperature for that fuel!
- Short answer: MUCH hotter than AIT for fuel vapors like gasoline
  - Depends on boiling point of liquid
  - Depends on nature of surface
  - Depends on viscosity
  - Depends on flammability range

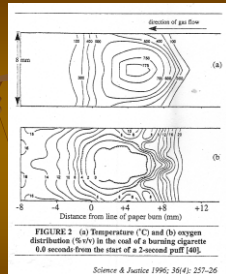
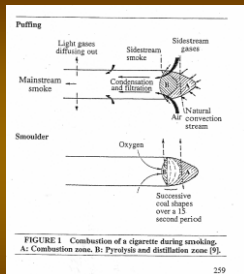


## Cigarettes and Gasoline!





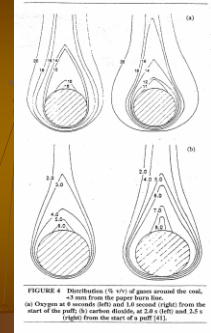
## Cigarette Ignition Fire Myths



- Temperature and Oxygen Concentration (from Holleyhead)
- Maximum coal temperatures are well above the AIT for gasoline, but...

## Cigarette Ignition Fire Myths

- The oxygen concentration in the coal is too low
- The quenching distance between ash/tobacco leaves too small
- Contact time between surface and vapor is ~1ms (needs ~20ms)
- Therefore, no ignition of gasoline vapors, BUT  $CS_2$ , hydrogen, and acetylene can be ignited due to their very low MIE.



## ■ Intermittent Sources

- Electrical Arcs – Switches, relays
- Hot Particles (How hot and how big?)

## Household Thermostats??



## Electric Motors??

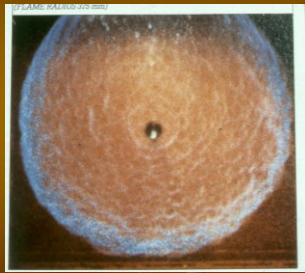


## What is the Most Dangerous Part of This Dryer for Vapor Ignition?



## Ignition in Uniform Mixture of Propane

- Arc ignition
- Spherical flame
- Wrinkled flame front



## Effects of Explosions

- 21.4: Explosion is a gas dynamic phenomenon that, under ideal theoretical circumstances will manifest itself as an expanding spherical heat and pressure-wave front.
- Like an expanding toy balloon, it can be distorted by confinement and squeezed through openings. The combustion rate is controlled by the surface area of the "balloon"
- See Fig. 21.4.1.1
- Effects of location of ignition – center, front, back

## DEFLAGRATIONS

Proceed Radially in all directions outward from the Ignition Source

Gathering Speed and Energy as the Flame Front

**EXPANDS**

## Explosive Effects

Are Produced by the Pressure Developing into a shock wave (of varying intensities)

Are Categorized by the Rate of Pressure Rise

## EXPANDING MASSES OF GASSES

From where do they come?

Molar ratios (pre- and post-combustion) for most hydrocarbon fuel vapors are 1.0 to 1.24

MOST expansion is due to **thermal** effects

## Molar Ratios

- Ratio of moles of post-reaction product to moles of reactant
- $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$  3:3 Ratio = 1
- $2\text{C}_2\text{H}_6 + 7\text{O}_2 \rightarrow 4\text{CO}_2 + 6\text{H}_2\text{O}$  10:9 Ratio = 1.1
- $\text{C}_3\text{H}_8 + 5\text{O}_2 \rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O}$  7:6 Ratio = 1.16
- $2\text{C}_4\text{H}_{10} + 13\text{O}_2 \rightarrow 8\text{CO}_2 + 10\text{H}_2\text{O}$  18:15 Ratio = 1.2
- $\text{C}_5\text{H}_{12} + 8\text{O}_2 \rightarrow 5\text{CO}_2 + 6\text{H}_2\text{O}$  11:9 Ratio = 1.22
- $2\text{C}_6\text{H}_{14} + 19\text{O}_2 \rightarrow 12\text{CO}_2 + 14\text{H}_2\text{O}$  26:21 Ratio = 1.24
- $\text{C}_4\text{H}_8 + 6\text{O}_2 \rightarrow 4\text{CO}_2 + 4\text{H}_2\text{O}$  8:7 Ratio = 1.14

## A Little Basic Thermodynamics

- Starting Temperature:
  - (Room Temperature): 300 K
- Final Temperature (Ideal Conditions):
  - 2300 K
- Ratio: 300:2300 ~ 8 Times , therefore,
  - 8 times the original Volume

## A Little Basic Physics

- Most containers , rooms, or buildings will **not** quickly expand to 8 times their original volume, so...
- The **pressure** goes up instead.
  - Per the universal gas law:  $pV = nRT$
- Maximum pressure for a hydrocarbon fuel is then 8 times atmospheric pressure or about 110 psi

## HAZARD ASSESSMENT

What happens when things go BANG?

## Effects of Explosions

### 21.4.1. Blast overpressure and Wave Effect

Positive pressure phase

Negative pressure phase

### 21.4.2 Shrapnel Effect (projectiles)

### 21.4.3 Thermal effect

### 21.4.4 Seismic effect

## BLAST EFFECTS !!!

**ACTUALLY**

**Pressure Effects**

## 921 Definitions

- 21.3: Characterization of explosion damage.  
(jd: NOT EXPLOSIVE FUNCTION)
- Low-order damage: walls, bulged out or laid down, virtually intact, next to the structure. Roofs lifted slightly...Windows may be dislodged, sometimes without the glass being broken. Debris is generally large and is moved short distances.
- High-order damage: Shattering of the structure, producing small debris pieces. Walls, roofs, and structural members are broken apart with some members splintered or shattered, and with the building completely demolished.

## Blast Effects

- Windows Fail at 0.2 to 1.0 psi  
(Depending on size, thickness, and style)
- Walls Fail at 1.0 to 5 psi  
(Depending on thickness and material)

Rate of pressure rise (impulse) is a factor in determining what moves or breaks

## Deflagrations: Large Pieces, Little Shattering



## Deflagrating Gasoline Vapor

- Large pieces
- Top to bottom
- Some scorching



## Deflagration Inside (Scorching)

- Scorching of walls
- Windows blown out plus wall
- Trash fire on floor was ignition source



## Deflagrating Explosion but...



- What's with the localized shattering and splintering?

## Examine All the Indicators



- Ah, a small high explosive charge used to scatter the gasoline and vaporize it.

## Blast Effects

- Some movement of lighter materials and rearrangement



## Natural Gas in Top Floor Apartment

- Gas meter by-passed
- Leaky connection
- Breakfast surprise

But how did windows on all those other floors get broken?



## Natural Gas (to excess)

- Wall of building opposite reflected the pressure pulse
- Ricochet, ricochet, ricochet!!



## Thermal Effects



Room before Coleman Fuel Deflagration

## Thermal Effects



Room after Coleman Fuel Deflagration

## Shrapnel Effects



Secondary Missiles Very Rare in Diffuse-Phase Explosions



## Shrapnel Effects

- From the outside, it was an energetic deflagration



## Gasoline Vapor: Own Goal



- Frame residence – omnidirectional explosion followed by fire

## Gasoline Vapor: Own Goal



- Ground level view – note fire damage

## Gasoline Vapor: Own Goal



- Our Hero – Crushed outside by falling wall

## Gasoline Vapor



- Our Hero - forgot gasoline evaporates on a hot day and the vapors flow out of open windows

## Gasoline Vapors



- Remains of M80 in hand – note burns

### Natural Gas – Lighter Than Air



- The School - Before

### Natural Gas – Lighter Than Air



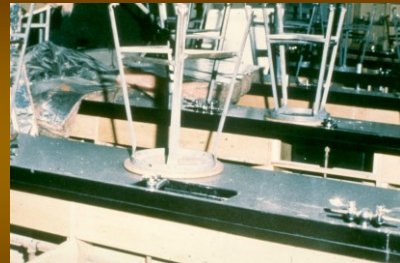
- The School - After

### Natural Gas – Lighter Than Air



- View Inside – Note Direction of Force

### Natural Gas – Lighter Than Air



- Roof-down Force – But what was the fuel?

### Natural Gas – Lighter Than Air

- Minimal Fire Damage – Lab Aprons



### Natural Gas – Lighter Than Air



- Massive Structural Damage Due to Steel Roof?

0530 – Loud noise!



Inside basement: scorching and sooting on walls



Blast damage on main floor very limited. Thermal damage to basement side of door



Floor deck shifted with charring of underside, high level thermal damage on basement walls



Scorching and melting indicates ignition source at heater

## Explosive Range







Aftermath: Massive fireball,  
extensive post-blast burning



Aerial view records omnidirectional  
distribution of pieces



Total destruction indicates lots of  
energy (fuel)



And here's Dad



Modest 18,000 sq. ft. house in Napa, up for sale.  
No takers at \$12 mill, reduced to \$9 mill



Commanding view, lake, tennis, large barn, 5 car garage



5:30AM on Sunday morning, big bang, then big fire (family on vacation, pets boarded). Note extent of debris field.



Not much left of structure except Chinese roof tiles and cement balustrades. The rest was wood frame, plywood, Styrofoam, and stucco

## Explosive Range

Window assemblies with draperies blown from second floor with no fire damage (identified from pre-fire photos)



## Explosive Range



Double-glazed windows blown out intact with frames

## Exploding Laundry Anyone?



- Is Mom surprised when laundry room door tries to leave via the front door!



Laundry room door blown off and adjacent wall penetrated from within





Ceiling of adjacent powder room punched downward



Thermal Damage to carpet only at door



Structural Damage to Doors, Walls, Ceilings

Washing machine cabinet most damaged



What was the Fuel and from Where?

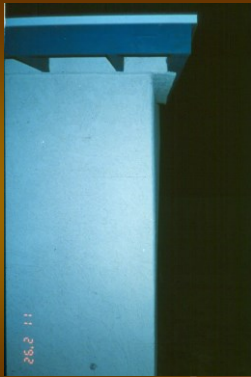
LPG – Lighter or Heavier?



Not from the house but from a can!

Phoenix: Explosion in house





Not much damage  
from outside ...  
but why is the  
ceiling sticking out  
?

## Living room

- Occupied at time
- Ceiling blown down from attic
- Fireball from kitchen



## Bedroom

- Walls shifted



Kitchen: Cabinets emptied, localized  
scorching



Aerosol cans, limited space, and an ignition  
source close by...



Drawers out, ceiling down, indicators of bug  
sprays



Son said mom was taping plastic over door opening and there's the proof



## AEROSOL CAN EXPLOSIONS

- Aerosol cans when heated can release their LPG propellant and cause significant structural damage

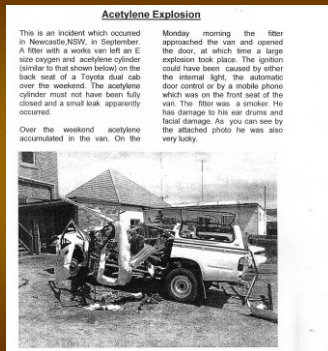


## COMBUSTION EXPLOSIONS

- Oakland Tribune 1/6/96
- Fix-A-Flat accidents killed several tire repairmen and injured many more.
- Luckily, no one was in this bed!
- This product no longer contains LPG



## VEHICLE EXPLOSIONS



## 921 Definitions

- 21.1.3.1: Hydrostatic Vessel Failure. The failure and bursting of a tank or vessel from hydrostatic pressure of a non-compressible fluid such as water is not an explosion, because the pressure is not created by gas. Explosions are gas dynamic.

## Mechanical Explosions

- Even When there is NO reaction
- Compressed Gases can still be Exciting in a Fire
- Aluminum Medical Oxygen Cylinder has no relief valve





## Compressed Gases in a Fire



## 921 Definitions

- 21.2.2: BLEVE. The boiling liquid, expanding vapor explosion is the type of mechanical explosion that will be encountered most frequently by the fire investigator. These are explosions involving vessels that contain liquids under pressure at temperatures above their atmospheric boiling points. The liquid need not be flammable.
- Old-style water heaters!



## Dry Ice, Acid or Gas Bombs

- May be mechanical explosion (dry ice to CO<sub>2</sub> or calcium carbide/water creating acetylene gas) or chemical explosion (acid or alkali and metal creating heat and gas)



## 921 Definitions

- 21.2.4: Electrical explosions. High-energy electrical arcs may generate sufficient heat to cause an explosion. The rapid heating of the surrounding gases results in a mechanical explosion that may or may not cause a fire. The clap of thunder accompanying a lightning bolt is an example of an electrical explosion.

## Other Chemical Hazards

Perchlorate mixed into precursor reacted with HI and Caused Explosion and Fire



## Flash Fire - Meth Lab



Trapped in lab for some time after flash



## Fatal Meth Lab



Protected areas from clothing?



## Honey Oil



Motel Room after Flash Fire

## Honey Oil



- Butane refills, extraction pipes, and MJ

## Honey Oil

- Extraction pipe
- Blender



## Honey Oil



- Signs of Occupation and Ignition Source?

## COMBUSTION EXPLOSIONS



- Thank you for your attention!
- Let's go blow something up (in the name of scientific research, of course)

## 21.14: INVESTIGATION

- First steps:
  - Secure scene – rescue/evacuation
  - Establish perimeter – initial survey – 1.5X distance of furthest obvious piece of debris.
  - Establish safety issues
  - Gather background/event info – interviews
  - Establish search pattern – size of scene, number of qualified searchers
    - Can be spiral, circular, grid or strip.
  - Select appropriate evidence markers – flags, cones, tents, cards (with nails)

## Initial Scene Assessment

- Evaluate explosive effects – type of debris, size of fragments, distance moved
- Does there appear to be an area of much more intense effects or crater (seated explosion) or directionality to debris field?
- Evaluate fire effects
  - Are remote fragments sooted, scorched or burned (pre-blast fire)?
  - Was there significant post-blast fire – generalized or localized?
- Possible ignition sources?

## Documentation

- Photographs of everything as found
- Measurements of debris – from apparent original location to where found
  - Laser 3D scans best
  - Total Station or tape measure
- Document possible sources of fuel and ignition
- Document debris clearance
- Diagram it ALL

## Physical Evidence

- Debris bearing possible residues
- Debris showing thermal effects
  - None, flame-washed, scorched overall, charred
- Possible fuel sources
- Possible ignition sources – including possible timing, delay, or remote-control devices
- Clothing of victims (living and deceased)

## 21.14.4 Detailed Scene Assessment

- Assess damage patterns and effects
- Map and diagram those variations
- Damage Effects:
  - Blast pressure and wave – positive phase
  - Blast pressure and wave – negative phase
  - Fragment impact
  - Thermal energy (including burns on victims)
  - Ground (seismic effects)
  - Dynamic drag loads (explosion wind)

## 21.14.3: Initial Assessment

- Fire effects v. Explosion Effects
- Start documentation
- Appears to be seated (crater) or non-seated (generalized, “omni-directional”)
- Possible classification: mechanical, chemical, BLEVE
- General fuel type: gas, vapor, dust, smoke
- Possible area(s) of origin (ignition)
- Possible ignition sources

### 21.14.4: Detailed Scene Assessment

- Map damage effects
- Map fragmentation distribution (debris fields)
- Pre- and post-blast fire effects
- Physical evidence
- Clothing of victims
  - May bear residues or fragments of significance

### Origin Determination

- May be area with LEAST physical damage
- In complex structures, more damage may occur away from source of ignition as flame "balloon" is distorted or confinement changes
- In long pipes or very long corridors, deflagrations of natural gas, propane, and acetylene can transition to detonations
- Crater:
  - very rare in diffuse-phase explosions
  - may occur in mechanical explosions or BLEVE's

### Ignition Sources

- Intermittent:
  - Electrical switches, relays (with open contacts)
  - Timers
  - Electronic or electric ignitors on gas appliances
  - Main burners on stoves, ovens, water heaters
  - Electric motors (old)
- Continuous:
  - Pilot lights
  - Candles

### Analyze and Diagram Movement

- See Figures 21.14.4.1.4 and 21.15 921
- Evaluate pressures needed to achieve injuries (Table 21.14.4.1.5(a))
  - Thermal injuries common
  - Moderate pressure blast injuries less common
  - Penetrating injuries from frag (shrapnel) rare in diffuse-phase deflagrations except for glass
- And observed damage (See Table 21.14.4.1(b))

### Analysis

- Evaluate all feasible hypotheses
- Correlate thermal damage patterns
- Correlate explosion damage and energies
- Evaluate physical evidence
- Identify fuel source and distribution
- Identify fuel source
- Identify cause mechanism